Agricultural and Forest Meteorology 248 (2018) 339–347

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

Climate-smart agroforestry: *Faidherbia albida* trees buffer wheat against climatic extremes in the Central Rift Valley of Ethiopia

Tesfaye Shiferaw Sida[a,c,*], Frédéric Baudron[b], Haekoo Kim[a], Ken E. Giller[c]

[a] International Maize and Wheat Improvement Center (CIMMYT)-Ethiopia, Shola Campus, ILRI, P.O. Box 5689, Addis Ababa, Ethiopia
[b] International Maize and Wheat Improvement Center (CIMMYT), Southern Africa Regional Office, P.O. Box MP 163, Mt Pleasant | 12.5 km Peg Mazowe Road, Harare, Zimbabwe
[c] Plant Production Systems, Wageningen University, P.O. Box 430, 6700 AK Wageningen, The Netherlands

ARTICLE INFO

Keywords:
Climate change
Local adaptation
Competition
Facilitation
Heat stress
Crop physiology

ABSTRACT

Faidherbia albida parklands cover a large area of the Sudano-Sahelian zone of Africa, a region that suffers from soil fertility decline, food insecurity and climate change. The parklands deliver multiple benefits, including fuelwood, soil nutrient replenishment, moisture conservation, and improved crop yield underneath the canopy. Its microclimate modification may provide an affordable climate adaptation strategy which needs to be explored. We carried out an on-farm experiment for three consecutive seasons in the Ethiopian Central Rift Valley with treatments of *Faidherbia* trees with bare soil underneath, wheat grown beneath *Faidherbia* and wheat grown in open fields. We tested the sensitivity of wheat yield to tree-mediated variables of photosynthetically active radiation (PAR), air temperature and soil nitrogen, using APSIM-wheat model. Results showed that soil moisture in the sub-soil was the least for wheat with tree, intermediate for sole tree and the highest for open field. Presence of trees resulted in 35–55% larger available N close to tree crowns compared with sole wheat. Trees significantly reduced PAR reaching the canopy of wheat growing underneath to optimum levels. Midday air temperature was about 6 °C less under the trees than in the open fields. LAI, number of grains spike^{-1}, plant height, total aboveground biomass and wheat grain yield were all significantly higher ($P < 0.001$) for wheat associated with *F. albida* compared with sole wheat. Model-based sensitivity analysis showed that under moderate to high rates of N, wheat yield responded positively to a decrease in temperature caused by *F. albida* shade. Thus, *F. albida* trees increase soil mineral N, wheat water use efficiency and reduce heat stress, increasing yield significantly. With heat and moisture stress likely to be more prevalent in the face of climate change, *F. albida*, with its impact on microclimate modification, maybe a starting point to design more resilient and climate-smart farming systems.

1. Introduction

Faidherbia albida (Del. A. Chev) trees are common features of the Sudano-Sahelian region of sub-Saharan Africa, forming 'parklands' (Bayala et al., 2014). 'Parklands', where scattered mature trees occur as an integral part of crop and livestock production landscapes, are one of the oldest agroforestry systems in Africa. They generate numerous provisioning and regulating ecosystem services (Sinare and Gordon, 2015), valuable assets in the economy of local communities (Mokgolodi et al., 2011) and socio-cultural values (Wahl and Bland, 2013). *Faidherbia* trees improve soil fertility through ecological process of nitrogen fixation (Giller, 2001), nutrient recycling (Sileshi, 2016) and accumulated soil organic matter (Gelaw et al., 2015). They improve water availability through different ecological processes such as hydraulic redistribution and improve water use efficiency of understorey crops (Bayala et al., 2015). Agroforestry has been suggested as an option to adapt to climate change (Matocha et al., 2012), which poses a serious threat to food security in smallholder agriculture (Mbow et al., 2014). According to a study from the Sahel, the parklands buffer climate risk and sustain agricultural production (Bayala et al., 2014), magnifying their importance under expected future climate change (Kassie et al., 2014). Despite these positive effects, trees in parkland systems also compete with crops for scarce resources (Bayala et al., 2015). Thus, research into management practices that maximize facilitation and minimize competition is needed. In the Central Rift Valley of Ethiopia, *Faidherbia* is the most common tree species, whereas wheat is the second most important crop after *teff* [*Eragrostis tef (Zucc.)* Trotter]. The current study focuses on unravelling the effects of interactions between

* Corresponding author at: Plant Production Systems, Wageningen University, P.O. Box 430, Wageningen, 6700 AK, The Netherlands.
E-mail addresses: tesfaye.sida@wur.nl, tesfayesida@gmail.com (T.S. Sida).

http://dx.doi.org/10.1016/j.agrformet.2017.10.013
Received 28 March 2017; Received in revised form 27 July 2017; Accepted 11 October 2017
Available online 19 October 2017
0168-1923/ © 2017 Elsevier B.V. All rights reserved.

Faidherbia and wheat. Frequent droughts and sparse use of fertilizer and improved seeds in the area cause extremely small crop yields (Van Halsema et al., 2011). Wheat yields average 1.4 t/ha, far below the yields of close to 5 t/ha reported from experimental stations (Abate et al., 2015). As crop yields are expected to fall further due to expected climate variability and change in the region (Kassie et al., 2014), these parkland systems could provide sustainable and affordable coping strategies for smallholder farmers with limited access to inputs (Lin, 2007).

F. albida is well known for its positive impacts on the productivity of the crop beneath its crowns (Mokgolodi et al., 2011). A unique 'reverse phenology' – i.e., shedding leaves during the crop growing season, which permits penetration of enough radiation for the understorey crops, has been understood to be one of the main reasons for the 'albida effect'. Although most of the 'albida effect' has been attributed to improved water and nutrient availability (Mokgolodi et al., 2011; Sileshi, 2016), Kho et al. (2001) hinted that the lower temperature under the canopy of *F. albida* could play an important role.

While the importance of such microclimate modification has been acknowledged, it has seldom been studied, especially under farmers' conditions. Similarly, detailed studies focusing on physiological responses of understorey crops are scarce. Microclimate modification by parkland trees was reported to benefit understorey herbaceous plants in savannah ecosystems (Ludwig et al., 2004), but can be outweighed with below-ground competition for annual crops (Kho et al., 2001; Van Noordwijk et al., 2015). Although trees reduce the quantity of incident radiation, which is directly related to dry matter accumulation in annual crops (Black and Ong, 2000), tree shades could buffer understorey crops against the predicted heat stress in the face of climate change. Thus, this study aims to quantify the impact of *F. albida* on the resources available to wheat (nutrients and water), on the microenvironment of wheat (temperature and radiation), and their impacts on the development and productivity of understorey wheat.

2. Materials and methods

2.1. Study area

The study area (Fig. 1) is located in the Central Rift Valley of Ethiopia (8°30′33" N and 39°04′16" E) at an elevation of 1665 m above sea level and has a flat topography. The climate is semi-arid with a potential evapotranspiration of 1305 mm yr^{-1} and an average annual rainfall of 700 mm yr^{-1} over the last decade (RSO, 2003). The rainy season generally starts in June and ends in September. The long term average mean minimum daily temperature is 24.2 °C and the mean maximum daily temperature is 31 °C. However, the maximum daily temperature often exceeds 35 °C during the cropping season (Van Halsema et al., 2011). Andosol is the dominant soil type, according to FAO soil taxonomy (RSO, 2003). Except for strong phosphate fixation, andosols are generally fertile with good nutrient content, aggregate stability and high porosity (Matus et al., 2014).

The natural vegetation in the area is classified as woodland and savannah, where *Acacia* species are commonly incorporated into the rain-fed farming system, forming 'parkland' agroforestry. *F. albida* is the main agroforestry species in fields where teff [*Eragrostis tef* (Zucc.) Trotter] is the most important crop, while wheat (*Triticum aestivum* L. *var aestivum*) is the second most important. The density (mean ± sd) of *F. albida* on the selected farms was 5.6 ± 1.3 trees ha^{-1}. The other dominant tree species in the area are: *Acacia tortilis*, *Acacia etbaica* and *Balanites aegyptiaca*, respectively (Iiyama et al., 2017). Wheat is generally planted early July and harvested late in October. In the study area, the 'reverse phenology' of *F. albida* is generally not observed. Heavy and frequent pruning of the trees towards the end of dry season (for fencing, charcoal and firewood production) apparently 'forces' the regeneration of green canopies during the crop growth period.

2.2. Experimental design and plot management

Tree-crop interaction was explored for wheat growing under crowns of scattered on-farm *F. albida,* replicated in three farms (Fig. 1). Two mature *F. albida* trees per farm were selected for an on-farm experiment. Selected pairs of trees were located in a single field within a farm and had approximately similar crown structures and pruning history (Table 1). For each tree, plots measuring 10 × 10 m were established with trees at the centre. Within the same field, another plot of the same size was established in an open field, at least 70 m away from any tree. This made a total of three plots per farm. Wheat was grown under the crown of one of the trees and in the open filed. The plot under the crown of the other tree remained bare. Treatments were designated as: 'tree with wheat' – for wheat grown under the canopy of *F. albida,* 'sole wheat' – for wheat grown in the open, and 'sole tree' – for *F. albida* without wheat. The experiment was replicated on three contrasting farms, creating a total of nine plots, and repeated for three seasons. Both trees and plots were managed following farmers' typical practices. Wheat variety 'Ude', which is well-adapted to semi-arid conditions, was used. Plots were fertilized with 64 kg ha^{-1} N (split applied 50% at sowing and the remaining side dressed at tillering) and 30 kg ha^{-1} P broadcast at sowing. Seed was drilled at a spacing of 20 cm between rows at the rate of 150 kg ha^{-1}. All plots were kept weed free. The experiment was conducted over three seasons from 2013 to 2015. Seasons 2013 (1001 mm yr^{-1}) and 2014 (727 mm yr^{-1}) had good rainfall, while 2015 was an El Niño season with 578 mm yr^{-1}, below the long-term average of 700 mm yr^{-1} for the area.

2.3. Soil sampling and analysis

Soil was sampled from all plots at depths of 0–10 cm, 10–20 cm and 20–40 cm at wheat grain filling stage, in 2014. For each depth and treatments, the samples were composited from three cores, oven-dried for 48 h at 60 °C and sieved to 2 mm. The composite bulk samples were analysed for $pH_{(water)}$, organic C (Walkley-Black), total N (micro Kjeldahl), P (Olsen), exchangeable K (Ammonium acetate method), and texture (hydrometric method) following procedures described in (Van Reeuwijk, 2008). Separate soil samples were collected using auger cores of known volume for bulk density determination. These samples were oven-dried at 105 °C for 24 h and weighed to determine bulk density. Soil nutrient contents were adjusted for bulk density during final mean comparison among treatments. Soil samples were also collected in the same manner at the end of dry season (May 2015) and available Nitrogen (NO_3-N) was analysed using a fast nitrate test method (Reflectoquant®, EM Science) following a procedure outlined in (Schmidhalter, 2005), where $CaCl_2$ was used as extracting agent.

2.4. Climatic, microclimatic and soil water data

Soil moisture was measured using Delta-T© moisture probes (Delta-T-Devices, 2013) at depths of 10, 20, 30, 40, 60 and 100 cm within pre-installed access tubes. The access tubes were installed at three distances from the tree trunk: under the tree crown (at 0.7 m and 6.2 m from the tree trunk) and outside the canopy i.e. in the sole wheat treatment (minimum of 70 m from the trunk of any surrounding tree). Soil moisture was measured twice a week during the cropping season (July–October) and twice a month during off-season (October–June). Tinytag© temperature loggers (Gemini-Instruments, 2013) from Gemini© instruments were installed at a height of 60 cm above-ground (approximately at the height where floral initiation and anthesis is expected for the wheat variety used), 0.7 m away from the trunk in the TW treatment and in the centre of the plot for the W treatment. Temperatures were recorded every 30 min starting from two weeks after wheat emergence (July) to harvesting (October) for all seasons (2013–2015). Photosynthetically active radiation (PAR) sensors from SunScan© Canopy Analysis System (Webb et al., 2013) were used to

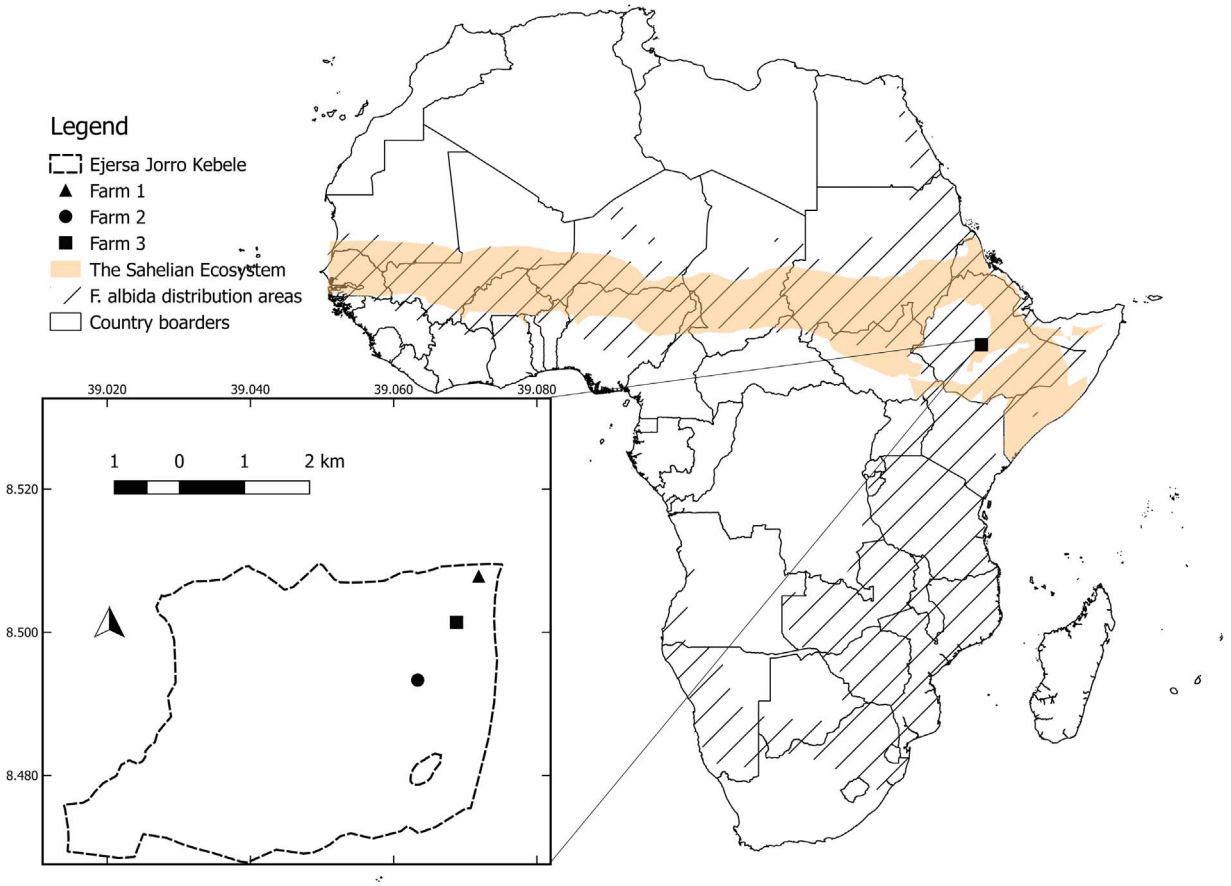

Fig. 1. Location of the study area in relation to the Sahelian ecosystem and the distribution area for *F. albida*. Ejersa Jorro is an administrative boundary where the landscape under study was located.

Table 1
Characteristics of *Faidherbia albida* trees under investigation. DBH = Diameter at breast height, DSH = Diameter at stump height, height = tree height to the tallest part of the canopy and CD = mean canopy diameter. Standard deviations from the means are given in the parenthesis.

		Tree Characteristics		
Treatment	DBH (cm)	DSH (cm)	Height (m)	CD (m)
Sole tree (n = 3)	43.8 (8.8)	46.2 (9.8)	10.7 (1.7)	11.8 (1.5)
Tree + Crop (n = 3)	44.3 (8.5)	45.5 (9.1)	10.7 (2.5)	11.7 (1.3)

measure PAR above and under wheat canopy for both 'tree with wheat (TW)' and 'sole wheat (W)' treatments. Measurements were taken at increasing distance from the tree trunk during midday at booting, anthesis and grain filling on cloudless days.

2.5. Crop parameters

In the 'tree with wheat' and 'sole wheat' treatments, days to 50% emergence, 50% tillering, 50% booting, 50% flowering, grain filling and physiological maturity were recorded. Leaf Area Index (LAI), number of tillers, plant height and number of senesced leaves were recorded weekly until physiological maturity. At harvest, plant height, number of fertile tillers per plant and number of grains per spike were recorded.

2.6. Data analysis and simulation modelling

Soil nutrient content and soil moisture content data were log-transformed for the data to follow normal distribution. For soil moisture, repeated measures ANOVA, also referred to as ANOVA for correlated samples, was used to analyse trends across treatments and depths at different days after planting. Tukey's HSD test was applied to find significant differences among treatments. We compared soil nutrient contents from under tree crowns and open fields using two-sample T-test. We carried out repeated measures ANOVA for air temperature logged between five days before 50% anthesis and end of milk stage. We made pairwise comparison for experiments with tree and without tree for 24 h, to identify the time of the day when temperature variation is the most pronounced. The same procedure was used to measure variations in photosynthetically active radiation (PAR). For PAR, we limited our analysis to means of the three measurements made at booting, anthesis and start of grain filling.

We compared LAI, number of tillers, number of senesced leaves, plant height, number of fertile tillers, number of grains spike^{-1}, total aboveground biomass and dry grain yield using independent samples *t*-test. For all the analyses, a probability level of 5% was used to test for significance. Only treatment means were collected during 2013 season, while data was disaggregated along distances from tree trunk for 2014 season. Thus, for trends across distance gradients, only the data from 2014 were used. Crop development was irregular and we included only the final yield and some environmental variables for season 2015, which was an El Niño season. Where complete data was available, it was presented over three seasons. All statistical analyses were conducted in R Core Team (2015).

2.7. Sensitivity analysis using Agricultural Production Systems sIMulator (APSIM) wheat module

The wheat crop model in APSIM 7.8.2 was calibrated using sole

wheat data from season 2013. Model validation was done using data from different treatments of season 2014. We used observed days to maturity, grains per g stem, maximum grain size, and potential grain filling rate in the calibration process, because the APSIM-wheat module was reported to be particularly sensitive to these parameters (Zhao et al., 2014). We also included observed soil moisture across wheat development stages in the calibration, as moisture stress could be the most important factor under the semi-arid condition of the current study area. In-season soil moisture and grain yield were used to validate the model. Validation showed reasonable fits for in-season soil moisture against predicted values with RMSE of 6.3 (mm) and $r^2 = 0.61$ (Appendix Fig. 1), and RMSE of 204.4 (kg ha^{-1}) and $r^2 = 0.75$ for observed grain yield against its corresponding predicted values (Appendix Fig. 2). We carried out sensitivity analysis with factorial combinations of three levels of radiation (−20%, −10% and observed), three levels of maximum temperature (−5 °C, observed and +2 °C), and three rates of N (0, 64 and 120 kg ha^{-1}). Graphs showing the sensitivity of wheat yield to factorial combinations of N, radiation, and temperature are presented as supplemental materials (Appendix Fig. 3a–c).

3. Results

3.1. Impact of F. albida on understorey resources (soil moisture and soil nutrients)

At planting (Fig. 2a), soil moisture in the topsoil did not show a clear trend across depth and treatments. For deeper profiles, there was a slightly larger moisture content for the sole tree (T) treatment compared with W and TW treatments. Towards the peak of wet season (Fig. 2b), soil moisture increased for all treatments and across all depths without clear influence of the treatments. At around peak grain filling (Fig. 2c), moisture content in the subsoil (30–60 cm) started to diverge between treatments. There was no such divergence in soil moisture content in the top soil (10–30 cm). In the subsoil, the least moisture was available in the TW and the most in the W treatments, except for the exceptional dry season of 2015. At harvest (Fig. 2d), there was relatively more soil moisture in the sole wheat treatment at greater depths, regardless of the general decline in moisture for all treatments.

At the end of 2013 cropping season, soil chemical parameters (soil organic C, total N, Olsen P and exchangeable K) and physical properties (bulk density and pH-H_2O) did not significantly differ in the soils under and outside the canopy of *F. albida* (Table 2).

On the other hand, at the end of dry season (May 2015) topsoil available NO_3-N decreased with increasing distance from the trunk of *F. albida* (Fig. 3a). This contrasts with the result in Table 2, where total SOM did not significantly vary in relation to the distance from tree crowns. However, no similar trend was observed at depths of 30–60 cm (Fig. 3a), where NO_3-N was more variable. In addition, NO_3-N did not change with distance at greater depths.

3.2. Impact of F. albida on understorey microclimate (PAR and temperature)

Another important localized resource – photosynthetically active radiation (PAR) – also varied due to shading by the trees. The recorded PAR was lower under the canopy than outside of *F. albida* (Fig. 3b). The reduction in PAR was much more variable under than outside the canopy whose influence extended to about 3.5 m from the tree trunk. Incident PAR close to the maximum of 2200 μmol m^{-2}s^{-1} was found above the wheat canopy in the open field at most measurement times.

Air temperature was lowered by up to 6 °C at midday under compared to outside the canopy of *F. albida* (Fig. 3c). Temperature reached 36 °C and was highly variable in the open field, while it reached a maximum of 29 °C and fluctuated less under the canopy. Temperature exceeded 28 °C, for about six hours day^{-1} (i.e., from 10:00–16:00 GMT) in the open fields and for less than two hours (i.e., from 12:300–14:300 GMT) for under the canopy. For close to three hours around midday (i.e. from 10:40-13:30 GMT), temperature was significantly cooler under tree crowns than in open fields ($P < 0.001$).

3.3. Crop development and productivity

Leaf senescence occurred earlier in wheat growing outside compared with under the canopy of *F. albida* (Table 3). Wheat under the canopy grew significantly more vigorously as illustrated by more tillers and larger LAI. Despite the significantly greater number of tillers under than outside tree crowns during vegetative stages, the number of fertile tillers at harvest was not significantly more (Table 3). Similarly, plants grew significantly taller under tree canopies than outside during earlier crop growth stages, although height was not significantly different at maturity (Table 3).

More grains per spike were recorded under compared with outside the canopy of *F. albida* (Table 4). Grain filling period was significantly longer under than outside the canopy of *F. albida* (Table 4). Simulations using long-term weather data demonstrated that most of the longer period of grain filling was due to lower temperatures under the canopy (Table 4). The decrease in mean maximum daily temperature by 5 ° slowed maturation of wheat (MDTM) by about 9 days. Almost all of the observed delay in duration to maturity (ODTM, also about 9 days) appeared to be attributed to the decrease in maximum temperature as a result of shading by *F. albida* crowns.

An average increase of 23–26% in grain yield and 20–39% in aboveground biomass was found under compared with outside the canopy during normal seasons of 2013 and 2014 (Table 4). While both yields were low in 2015, an El Niño year, an average increase of up to 85% in grain yield and 83% in aboveground biomass was found under compared with outside of the canopy (Table 4). Wheat grain yield and straw yield decreased exponentially with increasing distance from the tree trunk up to a distance of about 5.5 m (Fig. 4). Beyond this, yield of straw and grain was similar to that in the sole wheat.

3.4. Sensitivity of wheat productivity to microenvironment

In general, simulated wheat grain yield was more sensitive to changes in nitrogen rates than to changes in radiation or maximum temperature (Fig. 5). Without N added (0 kg ha^{-1}), simulated wheat grain yield was extremely small and showed no clear response to changes in temperature (Fig. 5a). With a medium N rate (64 kg ha^{-1}), an increase in maximum temperature by 2 °C resulted in an average yield decline of about 7% compared with yield simulated using observed maximum temperature (Fig. 5b). With this rate of N, a 5 °C reduction in maximum temperature had a positive impact on simulated wheat yield. Under this scenario, yield increase of about 16% was observed compared to yield simulated using observed maximum temperature.

With the highest N rate (120 kg ha^{-1}), a decrease from +2 to −5 °C in maximum temperature increased simulated grain yield by 36.9% in comparison to yield simulated for observed maximum temperature (Fig. 5c). An increase in maximum temperature by 2 °C resulted in about 12.5% decrease in yield compared with simulated yield using observed maximum temperature. Similarly, simulated yield was about 24.3% greater when the maximum temperature was decreased by 5 °C from the observed maximum.

4. Discussion

4.1. Partitioning, rather than competition, prevails in the F. albida-wheat interaction

A key question in tree-crop interaction in moisture stressed areas is whether the trees could absorb moisture from deeper horizons leaving more available topsoil moisture for annual crops. We observed no

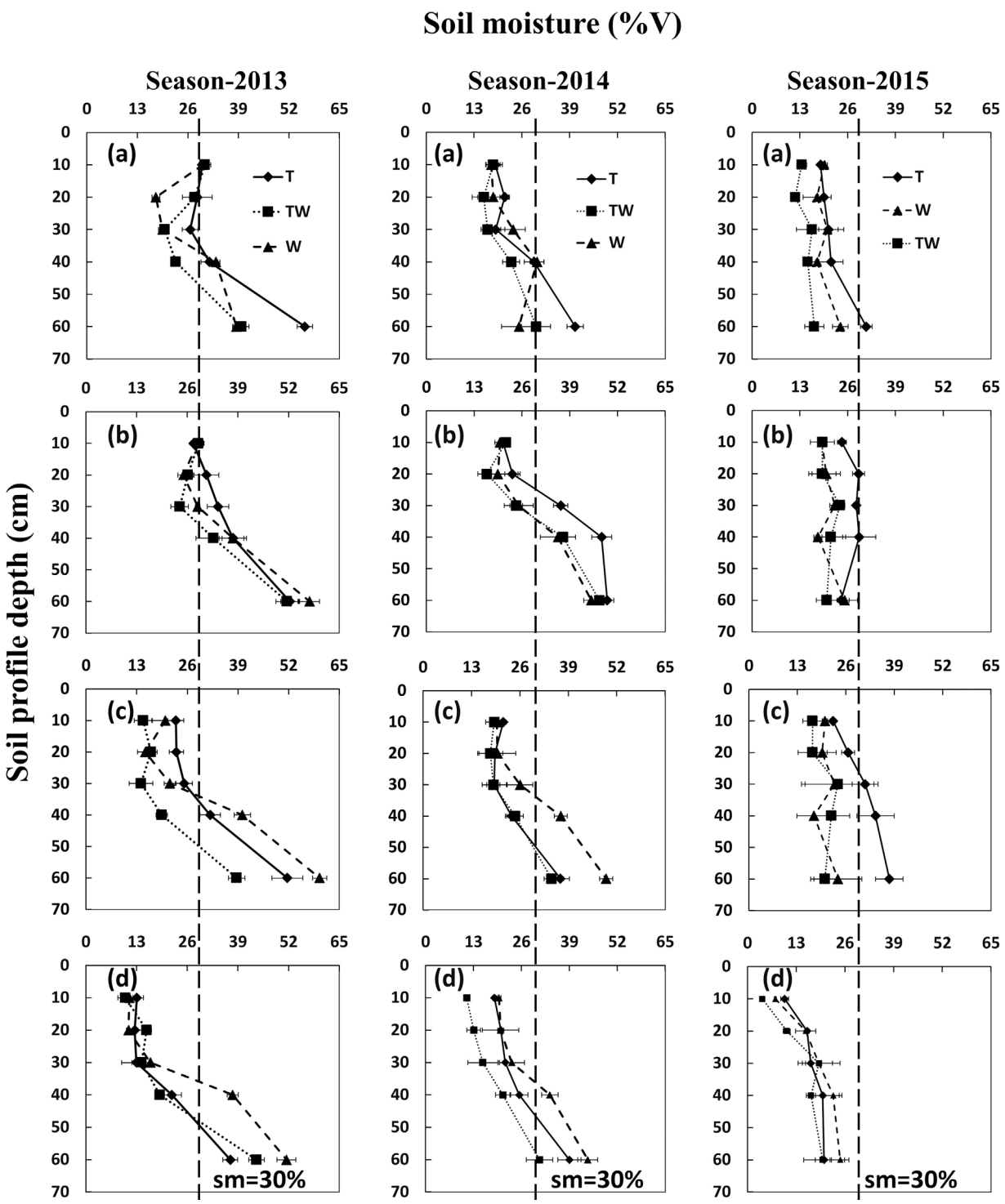

Fig. 2. Volumetric soil moisture content with depth at planting (a), 45 days after planting (b), 80 days after planting (c) and at maturity (d) in 2013, 2014 and 2015 for sole tree (T), wheat under tree crowns (TW) and sole wheat (W) treatments. 45 and 80 days represent vegetative and grain-filling stages, respectively of wheat. Broken vertical lines across the graph represent 30% by volume level of moisture content. Error bars are standard deviations.

variation in topsoil moisture content between treatments (Fig. 2). Because wheat tends to utilize moisture preferentially in the topsoil (Ngigi et al., 2006), a treatment with no wheat, i.e. sole tree, would be expected to exhibit extra moisture available in the topsoil. Both components (tree and wheat) can potentially extract moisture from the topsoil (Smith et al., 1997; Van Noordwijk et al., 2015). Thus, we expected the least moisture content in the topsoil would be found in treatments involving tree-crop interaction, which was not observed in the current study. While, this could suggest the absence of intensive competition for moisture in the topsoil, it could also be attributed to the reported reduction in evaporation from the soil surface under tree canopies, leading to greater soil moisture in the top soil (Lin, 2010).

On the other hand, at critical stage of grain filling (Fig. 2c), there was less moisture in deeper soil horizons when trees were present, except for the 2015 El Niño season where the tree alone treatment had more water in the subsoil. The tree roots apparently derive more of their moisture from deeper horizons hinting at 'niche differentiation' between tree and annual crop (García-Baquero et al., 2016). The

Table 2
Soil characteristics under and outside the canopy of *F. albida*. NS = non-significant effects. Standard deviations from the means are given in the parenthesis.

Treatments	Soil parameters					
	pH-H_2O	SOC (g/kg)	Total N (mg/kg)	Olsen P (mg/kg)	Exchangeable K (mmol/kg)	BD (g/cm^{-3})
Sole Wheat						
0–10 cm	6.73 (0.06)	10.95 (1.6)	8.56 (2.5)	1.97 (0.51)	1.45 (0.11)	1.14 (0.09)
10–20 cm	6.51 (0.65)	10.52 (2.6)	7.45 (2.2)	1.79 (0.45)	1.40 (0.18)	1.17 (0.21)
20–40 cm	7.06 (0.17)	7.71 (1.6)	5.27 (1.6)	1.36 (0.26)	1.36(0.30)	1.31 (0.09)
Wheat + *Faidherbia*						
0–10 cm	6.7 (0.24)	11.03 (1.1)	8.39 (0.8)	1.87 (0.35)	1.51 (0.2)	1.24 (0.03)
10–20 cm	6.89 (0.22)	9.49 (1.7)	7.09 (1.0)	1.88 (0.56)	1.46 (0.38)	1.21 (0.11)
20–40 cm	7.09 (0.17)	7.02 (1.9)	4.88 (2.3)	1.11 (0.34)	1.50 (0.56)	1.15 (0.05)
P-values*	NS	NS	NS	NS	NS	NS

* The *p*-values are for comparison of means from the two treatments at respective depth and not between depths of a single treatment. P-values of ns represent non-significant difference.

increasing gap in moisture contents (decreased under tree-wheat and increased for sole wheat) at greater depths in the soil indicates that the tree can extract more water from deeper layers. Smith et al. (1997) reported a similar finding, where trees extracted water from deeper soil profiles, while millet extracted water from the topsoil, especially during moisture stress periods.

In addition, sole trees had more moisture in deeper soil horizons and later in the seasons compared with tree-wheat treatments, supporting the notion that niche differentiation could be driven by competition for moisture (García-Baquero et al., 2016). Late in the season when ground water table recedes and competition for soil moisture is likely to intensify between tree and crop roots, deep-penetrating roots of *F albida* can capture moisture from deeper soil horizons (Canham et al., 2012). This would enable the shallow-rooted wheat to extract soil moisture in the top soil with minimal competition from tree roots. Thus, the association of the two species utilized more water than any of the two species in isolation, implying that systems that involve trees have increased water use efficiency. This corroborates previous reports from other systems, where presence of trees increased resource capture in maze systems (Lott et al., 2009).

Although soil fertility improvement effects of parkland trees are well established (Boffa, 1999; Kho et al., 2001; Gelaw et al., 2015; Sileshi, 2016), we found no evidence of enhanced soil organic matter under the canopy of *F. albida*. Yet, we did measure increased concentrations of available mineral N under the tree crowns (Fig. 3a). Yengwe et al. (2017) also found faster rates of N mineralization close to F. *albida* crowns. However, it has been contested whether trees actually increase soil fertility or redistribute it (Bayala et al., 2014), although N2-fixing trees such as *F. albida* undoubtedly add N to the production system (Giller, 2001).

4.2. F. albida buffers wheat against extreme temperatures and radiations

Our conclusion that resource partitioning may improve the productivity of understorey annuals concurs with studies from savannah (Ludwig et al., 2004), the Sahelian parklands (Kho et al., 2001) and other tropical agricultural systems (Black and Ong, 2000). Whether the improved nitrogen and soil moisture under crowns lead to enhanced productivity depends on the impact of trees on the understorey microenvironment. *F. albida* buffered wheat against heat stress at critical

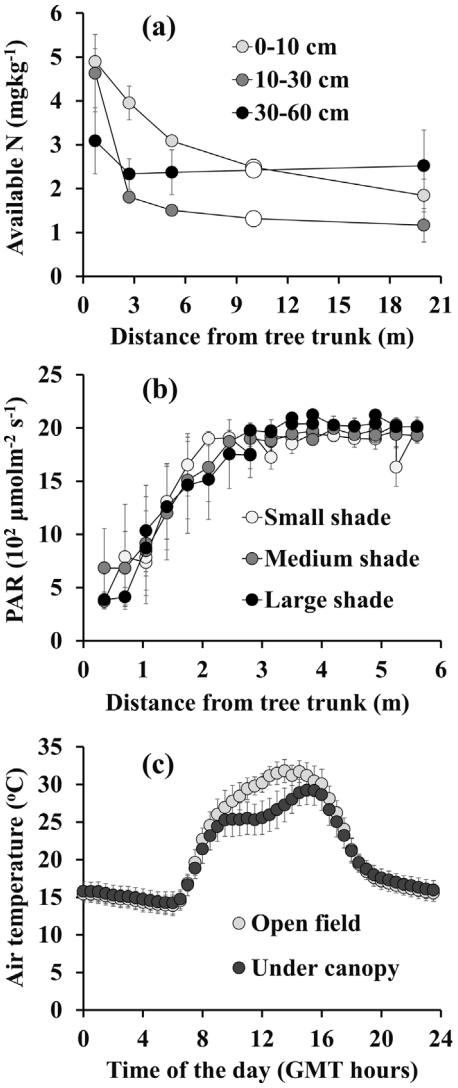

Fig. 3. Localized microenvironment modification by *F. albida:* available nitrogen (a), photosynthetically active radiation (PAR) (b) as a function of distance from the trunk of trees and diurnal variation in air temperature under and outside the canopy of *F. albida* between anthesis and grain filling stages (c). Graphs were generated from the means of two seasons, except for available nitrogen. The error bars are standard deviations.

reproductive stages (anthesis-grain filling). Peak temperatures above 28 °C for consecutive days can slow development in wheat, especially during reproductive stages (Fischer, 2011; Lobell et al., 2012). Such temperatures, which are common in the study area, could result in heat stress that reduces spike length and the number of seeds per spike (Acreche and Slafer, 2009), leading to significantly less grain yield (Zhao et al., 2014). In addition, reduced heat stress optimizes photosynthetic rates (Al-Karaki, 2012). Under projected climate change scenario, temperature in the area is expected to increase in the range of 1.4–4.1 °C by 2080 (Kassie et al., 2014). Such variation in temperature was reported to cause about 50% reduction in wheat grain yield (Asseng et al., 2011), magnifying the importance of *F. albida* trees as an affordable and locally available adaptation strategy (Lin, 2007; Mbow et al., 2014).

Simulation results suggest the lower temperature also explains the longer grain filling period for wheat under the canopy of *F. albida* compared with sole wheat (Table 4). High temperatures shorten the duration of the pre-anthesis period in wheat (Al-Karaki, 2012). Shortening of the growing season, resulting in more rapid crop maturity and reduction in yield, is one of the challenges from climate change on agricultural production (Anwar et al., 2015). *F. albida* shade moderates

Table 3
Crop growth parameters at different physiological stages for sole wheat and wheat under the canopy of *F. albida* in 2014. DAP = days after planting and LAI = Leaf area index, SL = Senesced leaves and No = number. Standard deviations from the mean are given in the parenthesis.

Treatments	Crop growth parameters			
	Tillers[a] (No plant $^{-1}$)	Plant height (cm)	LAI	SL (No plant $^{-1}$)
30 DAP				
Sole Wheat	2.55 (1.3)	26.59 (3.8)	1.9 (0.9)	–
Wheat + *Faidherbia*	2.77 (1.2)	28.94 (3.7)	2.4 (1.2)	–
P-values	0.087	**0.000**	**0.000**	–
40 DAP				
Sole Wheat	3.47 (1.9)	34.46 (5.3)	4.7 (1.6)	2.08 (0.09)
Wheat + *Faidherbia*		36.0 (4.2)	5.7 (2.3)	1.01(0.12)
P-values	*0.14*	***0.001***	***0.000***	*0.184*
60 DAP				
Sole Wheat	4.27 (2.7)	71.98 (6.4)	7.8 (2.5)	3.75 (0.96)
Wheat + *Faidherbia*		69.22 (8.3)	8.6 (3.4)	2.22 (0.70)
P-values	***0.000***	***0.000***	***0.012***	***0.007***
Harvest[b]				
Sole Wheat	4.0 (1.4)	70.3 (2.2)	–	–
Wheat + *Faidherbia*	4.2 (1.6)	73.4 (2.6)	–	–
P-values	*0.388*	*0.213*	–	–

[a] Tillers per plant at harvest represent the number of fertile tillers.
[b] All values at harvest represent the mean values of the 2013 and 2014 seasons.

Table 4
Final yield and yield components for wheat grown under and outside the canopy of *F. albida* for three consecutive seasons. ODTM = Observed duration to maturity and MDTM = Modeled duration to maturity. Standard deviations from the means are given in the parenthesis.

Treatments	Wheat yield and yield components				
	Grains (spike$^{-1)}$	Total biomass (t/ha)	Grain yield (t/ha)	ODTM (days)	MDTM[a] (days)
2013 season					
Sole wheat	39.7 (1.7)	5.7 (1.2)	1.9 (0.3)	103	100
Wheat + *Faidherbia*	42.3 (2.5)	7.9 (0.7)	2.4 (0.2)	111	110
P-values	***0.021***	***0.002***	***0.002***	***0.000***	–
2014 season					
Sole wheat	40.5 (3.7)	7.4 (1.5)	2.6 (0.8)	101	96
Wheat + *Faidherbia*	42.8 (3.4)	8.9(1.6)	3.3 (0.7)	113	107
P-values	***0.000***	***0.000***	***0.000***	***0.000***	–
2015 season[b]					
Sole wheat	N/A	1.8 (1.0)	0.7 (0.4)	97	90
Wheat + *Faidherbia*	N/A	3.3 (1.3)	1.3 (0.6)	104	97
P-values		***0.000***	***0.000***	***0.000***	–

[a] MDTM for 'wheat + Faidherbia' was simulated by lowering daily mean maximum temperature 5°, keeping all the other variables constant.
[b] 2015 season was an El Nino season, where wheat yield was very low, but still better closer to tree canopies. Other parameters were not included in the analysis for this season.

wheat against such heat extremes, increasing the duration of these period, hence increased productivity in wheat.

F. albida moderated wheat against the excessive radiation in this semi-arid area (Fig. 3b). A PAR up to 2200 μmol $m^{-2}s^{-1}$ measured from outside *F. albida* shade for most of the season is above the optimum for wheat (Motzo et al., 2013). Such intense radiation causes photo-inhibition during biomass accumulation in wheat (Acreche and Slafer, 2009), causing decreased aboveground biomass. Similarly,

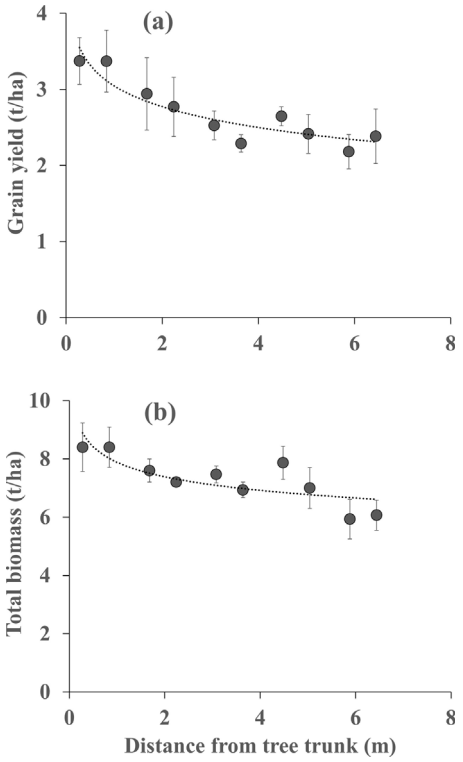

Fig. 4. Grain yield (a) and total aboveground biomass (b) as a function of distance from the trunk of *F. albida*in 2014. The error bars represent the standard deviations.

improved maize yield as a result of microclimate modification was reported from other tree-based systems (Black and Ong, 2000).

4.3. *F. albida* delays wheat senescence and lengthens grain filling

Slower leaf senescence was observed when wheat was grown under tree compared with wheat in full sun (Table 3). Leaf senescence in wheat is a physiological adaptation to moisture and heat stress (Motzo et al., 2013). Delayed senescence, perhaps as a result of shade, increases rate and duration of photosynthesis, enhancing assimilation and dry matter accumulation (Al-Karaki, 2012; Sanou et al., 2012). In turn, a lengthened grain filling period (Table 4) allows wheat to use more resources (water and nutrients) and produce heavier grains (Lobell et al., 2012). Although delayed grain filling may have a negative impact on productivity when soil moisture (Fischer, 2011; Lobell et al., 2012) or other resources (Anwar et al., 2015) are limiting, it can be beneficial when sufficient water and nutrients are available to utilize.

4.4. *F. albida* improves overall productivity of wheat

A larger leaf area of wheat under the canopy of *F. albida* (Table 3) could result in more wheat aboveground biomass (Guendouz et al., 2016). Although there were significantly more tillers during the vegetative stage under crowns (Table 3), we did not observe significantly more fertile tillers at harvest. Perhaps more abortion occurred under than outside the canopy, which is common for wheat under terminal stress (Al-Karaki, 2012). However, infertile tillers still contribute to more biomass. While Fischer (2011) reported that the number of grains per spike is negatively related to the number of tillers, our result suggested that wheat under *F. albida* shade apparently overcame this by reducing its spike fertility index i.e a greater proportion of infertile tillers compared with wheat in the open. Grain development is strongly affected by moisture and heat stress during anthesis and pre-anthesis (Fischer, 2011; Al-Karaki, 2012). The buffering effects of *F. albida*, increasing moisture availability and limiting heat stress during these

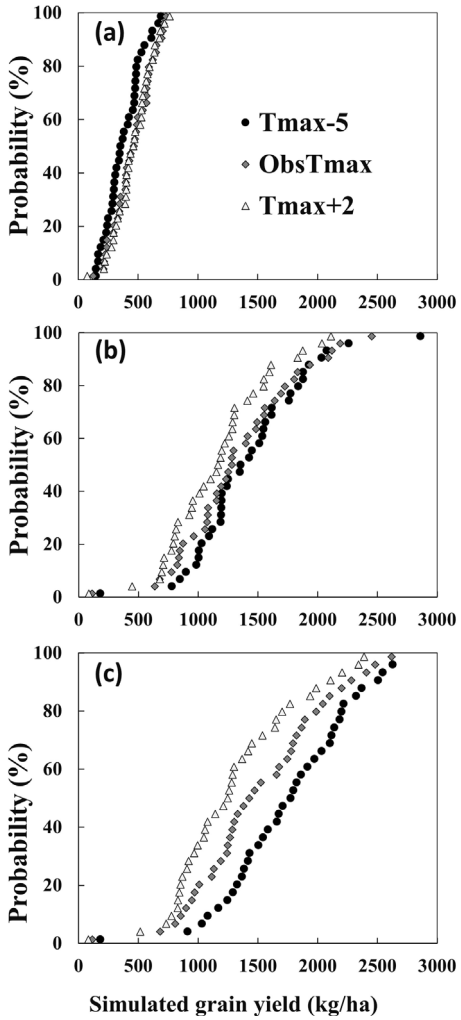

Fig. 5. Cumulative probability distribution of simulated wheat yield (using APSIM) for three levels of maximum temperature (maximum temperature reduced by 5 °C (Tmax-5), observed maximum temperature (ObsTmax) and maximum temperature increased by 2 °C (Tmax + 2)) and three nitrogen rates (0 kg ha^{-1} (a), 69 kg ha^{-1} (b) and 120 kg ha^{-1}(c)) for 38 rainy seasons (from 1977 to 2015). Simulations with factorial combination of radiation, temperature and N rates are given in Fig. S3 of supplemental material.

stages, could have facilitation effects for wheat under the canopy.

The yield reduction we observed with increasing distance up to about 5 m from tree trunk contradicts previous studies, which found maximum yield close to the canopy edge for millet (Boffa, 1999; Kho et al., 2001; Sanou et al., 2012). This could probably be attributed to three main reasons. First, the heavy pruning of *F. albida* in the study area might reduce the effect of shading on crop growth, contrasting with the large canopy of unpruned trees in other regions (Boffa, 1999). Second, compared with millet, the C3 wheat could tolerate shade better, leading to better performance closer to tree trunk. Third, the inherently porous soil of the current study area may enhance better infiltration under tree canopies, leading to higher infiltration around the canopy edges than in open fields, compared with soils with poor structures common in the other drylands (Bargués Tobella et al., 2014).

4.5. Wheat yield is highly sensitive to N and slightly sensitive to reduced temperature

Without applied N (Fig. 5a), simulated wheat grain yield was extremely small and did not respond to changes in temperature regimes. While increasing N rate strongly increased yield, reduced temperature, which is observed under *F. albida* shade, has a positive impact on wheat yield. An extended grain filling stage (Table 4) is one of the ways that lowered temperature improves yield (Craufurd and Wheeler, 2009). However, delayed phenology could potentially reduce wheat yield where resources (soil water and nutrients) are limited (Fischer, 2011; Lobell et al., 2012; Kassie et al., 2014; Anwar et al., 2015). By contrast, *F. albida* delays the phenology of wheat, whilst providing it with more resources (water and available nitrogen) under the tree.

4.6. F. albida in the context of sustainable intensification and adaptation to climate change

In the Central Rift Valley of Ethiopia, temperature is predicted to increase at the rate of 0.12–0.54 °C per decade and crop growing season will be shortened to about 76 days (Kassie et al., 2014). At this rate, temperature in the year 2100 would be about 4.1 °C higher compared with 1980. Similar predictions exist for sub-Saharan Africa and the Sahel (New et al., 2011). With climate change impact of such magnitude, most farming systems in the region are predicted to collapse, unless they undergo transformational adaptation (New et al., 2011; Rickards and Howden, 2012). While Challinor et al. (2014) classified crop-level adaptations of existing cropping systems, such as changes in varieties, planting times, irrigation and residue management as typically 'incremental', shifting from sole cereals to farm forestry, leading to a relatively profound change in the system could offer a transformational adaptation option (Rickards and Howden, 2012). Major and purposeful action at national level, such as the plan by the government of Ethiopia to incorporate 100 million *F. albida* trees into smallholder farming systems (Mekonnen et al., 2013) has a potential to achieve this. *F. albida* based systems could provide a triple benefit of climate change mitigation (Bayala et al., 2006), ecosystem based-adaptation (Matocha et al., 2012) and improved food security (Mokgolodi et al., 2011; Mbow et al., 2014).

5. Conclusion

Scattered *F. albida* trees improve wheat productivity significantly by buffering the crop against extreme temperature and by facilitating increased water use efficiency. With heat and moisture stress likely to be more prevalent in the face of climate change, these trees provide a starting point to design more resilient and climate smart farming systems. The facilitative impacts were found to be localized close to the tree trunk and were more pronounced during extremely dry season. In addition to its positive impact on wheat productivity, trees at the same time would provide more feed, fuel and construction material, as well as other ecosystem services (carbon sequestration, reduced soil erosion, habitat, etc.). This is a rare triple win for climate smart agriculture, providing enhanced productivity and adaptation while contributing to mitigation in the face of climate change.

Acknowledgements

This work was implemented by CIMMYT and Wageningen University as part of the project 'Trees for Food Security' (FSC/2012/014), made possible by the generous support of the Australian Centre for International Agricultural Research (ACIAR) and CRP WHEAT (www.wheat.org). Any opinions, findings, conclusion, or recommendations expressed in this publication are those of the authors and do not necessarily reflect the view of ACIAR and CRP MAIZE. We acknowledge the Ethiopian Institute of Agricultural Research (EIAR) for supporting the implementation on-farm experiments.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.agrformet.2017.10.013.

References

Abate, G.T., de Brauw, A., Minot, N., Tanguy, B., 2015. The Impact of the Use of New Technologies on Farmers' Wheat Yield in Ethiopia: Evidence from a Randomized Controlled Trial.

Acreche, M.M., Slafer, G.A., 2009. Grain weight: radiation interception and use efficiency as affected by sink-strength in Mediterranean wheats released from 1940 to 2005. Field Crops Res. 110, 98–105.

Al-Karaki, G.N., 2012. Phenological development-yield relationships in durum wheat cultivars under late-season high-temperature stress in a semiarid environment. ISRN Agron. 2012.

Anwar, M.R., Li Liu, D., Farquharson, R., Macadam, I., Abadi, A., Finlayson, J., Wang, B., Ramilan, T., 2015. Climate change impacts on phenology and yields of five broadacre crops at four climatologically distinct locations in Australia. Agric. Syst. 132, 133–144.

Asseng, S., Foster, I., Turner, N.C., 2011. The impact of temperature variability on wheat yields. Global Change Biol. 17, 997–1012.

Bargués Tobella, A., Reese, H., Almaw, A., Bayala, J., Malmer, A., Laudon, H., Ilstedt, U., 2014. The effect of trees on preferential flow and soil infiltrability in an agroforestry parkland in semiarid Burkina Faso. Water Resour. Res. 50, 3342–3354.

Bayala, J., Balesdent, J., Marol, C., Zapata, F., Teklehaimanot, Z., Ouedraogo, S., 2006. Relative contribution of trees and crops to soil carbon content in a parkland system in Burkina Faso using variations in natural 13C abundance. Nutr. Cycl. Agroecosyst. 76, 193–201.

Bayala, J., Sanou, J., Teklehaimanot, Z., Kalinganire, A., Ouédraogo, S.J., 2014. Parklands for buffering climate risk and sustaining agricultural production in the Sahel of West Africa. Curr. Opin. Environ. Sustain. 6, 28–34.

Bayala, J., Sanou, J., Teklehaimanot, Z., Ouedraogo, S., Kalinganire, A., Coe, R., vanNoordwijk, M., 2015. Advances in knowledge of processes in soil–tree–crop interactions in parkland systems in the West African Sahel: a review. Agric. Ecosyst. Environ. 205, 25–35.

Black, C., Ong, C., 2000. Utilisation of light and water in tropical agriculture. Agric. Forest Meteorol. 104, 25–47.

Boffa, J.-M., 1999. Agroforestry Parklands in Sub-Saharan Africa. FAO Rome.

Canham, C.A., Froend, R.H., Stock, W.D., Davies, M., 2012. Dynamics of phreatophyte root growth relative to a seasonally fluctuating water table in a Mediterranean-type environment. Oecologia 170, 909–916.

Challinor, A.J., Watson, J., Lobell, D., Howden, S., Smith, D., Chhetri, N., 2014. A meta-analysis of crop yield under climate change and adaptation. Nat. Clim. Change 4, 287.

Craufurd, P.Q., Wheeler, T., 2009. Climate change and the flowering time of annual crops. J. Exp. Bot. 60, 2529–2539.

Delta-T-Devices, 2013. User Manual for the Profile Probe (type ML3). Delta-T Devices Ltd., Cambridge, UK.

Fischer, R., 2011. Wheat physiology: a review of recent developments. Crop Pasture Sci. 62, 95–114.

García-Baquero, G., Silvertown, J., Gowing, D.J., Valle, C.J., 2016. Dissecting the hydrological niche: soil moisture, space and lifespan. J. Veg. Sci. 27, 219–226.

Gelaw, A.M., Singh, B., Lal, R., 2015. Organic carbon and nitrogen associated with soil aggregates and particle sizes under different land uses in Tigray, Northern Ethiopia. Land Degrad. Dev. 26, 690–700.

Gemini-Instruments, 2013. User Mannual for Tinytag Tempercher Loggers: Type Veiw 2. Gemini Instruments Ltd., Chichester, UK.

Giller, K.E., 2001. Nitrogen Fixation in Tropical Cropping Systems. Cabi.

Guendouz, A., Semcheddine, N., Moumeni, L., Hafsi, M., 2016. The effect of supplementary irrigation on leaf area specific leaf weight, grain yield and water use efficiency in durum wheat (Triticum durum Desf.) cultivars. Ekin J. 2, 82–89.

Iiyama, M., Derero, A., Kelemu, K., Muthuri, C., Kinuthia, R., Ayenkulu, E., Kiptot, E., Hadgu, K., Mowo, J., Sinclair, F.L., 2017. Understanding patterns of tree adoption on farms in semi-arid and sub-humid Ethiopia. Agrofor. Syst. 91, 271–293.

Kassie, B., Rötter, R., Hengsdijk, H., Asseng, S., Van Ittersum, M., Kahiluoto, H., Van Keulen, H., 2014. Climate variability and change in the Central Rift Valley of Ethiopia: challenges for rainfed crop production. J. Agric. Sci. 152, 58–74.

Kho, R., Yacouba, B., Yayé, M., Katkoré, B., Moussa, A., Iktam, A., Mayaki, A., 2001. Separating the effects of trees on crops: the case of Faidherbia albida and millet in Niger. Agrofor. Syst. 52, 219–238.

Lin, B.B., 2007. Agroforestry management as an adaptive strategy against potential microclimate extremes in coffee agriculture. Agric. Forest Meteorol. 144, 85–94.

Lin, B.B., 2010. The role of agroforestry in reducing water loss through soil evaporation and crop transpiration in coffee agroecosystems. Agric. Forest Meteorol. 150, 510–518.

Lobell, D.B., Sibley, A., Ivan Ortiz-Monasterio, J., 2012. Extreme heat effects on wheat senescence in India. Nature Clim. Change 2, 186–189.

Lott, J., Ong, C., Black, C., 2009. Understorey microclimate and crop performance in a Grevillea robusta-based agroforestry system in semi-arid Kenya. Agric. Forest Meteorol. 149, 1140–1151.

Ludwig, F., de Kroon, H., Berendse, F., Prins, H.H., 2004. The influence of savanna trees on nutrient, water and light availability and the understorey vegetation. Plant Ecol. 170, 93–105.

Matocha, J., Schroth, G., Hills, T., Hole, D., 2012. Integrating Climate Change Adaptation and Mitigation Through Agroforestry and Ecosystem Conservation. Agroforestry-The Future of Global Land Use. Springer, pp. 105–126.

Matus, F., Rumpel, C., Neculman, R., Panichini, M., Mora, M., 2014. Soil carbon storage and stabilisation in andic soils: a review. Catena 120, 102–110.

Mbow, C., Van Noordwijk, M., Luedeling, E., Neufeldt, H., Minang, P.A., Kowero, G., 2014. Agroforestry solutions to address food security and climate change challenges in Africa. Curr. Opin. Environ. Sustain. 6, 61–67.

Mekonnen, K., Amede, T., Duncan, A., Gebrekirstos, A., 2013. Sustainable agricultural intensification and its role on the climate resilient green economy initiative in Ethiopia. In: Report of the 3rd National Platform Meeting on Land and Water Management in Ethiopia. Addis Ababa, 23–24 July, 2012.

Mokgolodi, N.C., Setshogo, M.P., Shi, L.-l., Liu, Y.-j., Ma, C., 2011. Achieving food and nutritional security through agroforestry: a case of Faidherbia albida in sub-Saharan Africa. For. Stud. China 13, 123–131.

Motzo, R., Pruneddu, G., Giunta, F., 2013. The role of stomatal conductance for water and radiation use efficiency of durum wheat and triticale in a Mediterranean environment. Eur. J. Agron. 44, 87–97.

New, M., Liverman, D., Schroder, H., Anderson, K., 2011. Four Degrees and Beyond: the Potential for a Global Temperature Increase of Four Degrees and Its Implications. The Royal Society.

Ngigi, S.N., Rockström, J., Savenije, H.H.G., 2006. Assessment of rainwater retention in agricultural land and crop yield increase due to conservation tillage in Ewaso Ng'iro river basin, Kenya. Phys. Chem. Earth, Parts A/B/C 31, 910–918.

R Core Team, 2015. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. http://www.R-project.org/.

RSO, 2003. Regional Government of Oromia. Lume Woreda Based Development Programme. Oromia Economic Study Project Office, Mojo.

Rickards, L., Howden, S., 2012. Transformational adaptation: agriculture and climate change. Crop Pasture Sci. 63, 240–250.

Sanou, J., Bayala, J., Bazie, P., Teklehaimanot, Z., 2012. Photosynthesis and biomass production by millet (Pennisetum glaucum) and taro (Colocasia esculenta) grown under baobab (Adansonia digitata) and néré (Parkia biglobosa) in an agroforestry parkland system of Burkina Faso (West Africa). Exp. Agric. 48, 283–300.

Schmidhalter, U., 2005. Development of a quick on-farm test to determine nitrate levels in soil. J. Plant Nutrit. Soil Sci. 168, 432–438.

Sileshi, G.W., 2016. The magnitude and spatial extent of influence of Faidherbia albida trees on soil properties and primary productivity in drylands. J. Arid Environ. 132, 1–14.

Sinare, H., Gordon, L.J., 2015. Ecosystem services from woody vegetation on agricultural lands in Sudano-Sahelian West Africa. Agric. Ecosyst. Environ. 200, 186–199.

Smith, D.M., Jarvis, P.G., Odongo, J.C., 1997. Sources of water used by trees and millet in Sahelian windbreak systems. J. Hydrol. 198, 140–153.

Van Halsema, G., Keddi Lencha, B., Assefa, M., Hengsdijk, H., Wesseler, J., 2011. Performance assessment of smallholder irrigation in the Central Rift Valley of Ethiopia. Irrig. Drain. 60, 622–634.

Van Noordwijk, M., Lawson, G., Hairiah, K., Wilson, J., 2015. Root Distribution of Trees and Crops: Competition And/or Complementarity. Tree?Crop Interactions: Agroforestry in a Changing Climate. CABI, Wallingford, UK, pp. 221–257.

Van Reeuwijk, L., 2008. Procedures for Soil Analysis. Technical Paper 9. ISRIC, Wageningen.

Wahl, C.T., Bland, W.L., 2013. Faidherbia albida on the Tonga Plateau of southern Zambia: an agroecological analysis. Int. J. Agric. Sustain. 11, 382–392.

Webb, N., Nichol, C., Wood, J., Potter, E., 2013. User Manual for the SunScan Canopy Analysis System, Type SS1, Version: 2.0. Delta-T Devices Ltd, Cambridge, UK, pp. 83.

Yengwe, J., Gebremikael, M.T., Buchan, D., Lungu, O., De Neve, S., 2017. Effects of Faidherbia albida canopy and leaf litter on soil microbial communities and nitrogen mineralization in selected Zambian soils. Agrofor. Syst. 1–15.

Zhao, G., Bryan, B.A., Song, X., 2014. Sensitivity and uncertainty analysis of the APSIM-wheat model: interactions between cultivar, environmental, and management parameters. Ecol. Modell. 279, 1–11.